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Review

Nuclear energy: Between global electricity demand, worldwide decarbonisation imperativeness, and planetary environmental implications

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ABSTRACT

For decades, nuclear energy has been considered an important option for ensuring global energy security, and it has recently started being promoted as a solution for climate change mitigation. However, nuclear power remains highly controversial due to its associated risks – nuclear accidents and problematic radioactive waste management. This review aims to assess the viability of global nuclear energy economically (energy-wise), climatically and environmentally. To this end, the nuclear sector's energy- and climate-related advantages were explored alongside the downsides that mainly relate to radioactive pollution. Economically, it was found that nuclear energy is still an important power source in many countries around the world. Climatically, nuclear power is a low-carbon technology and can therefore be a viable option for the decarbonization of the world's major economies over the following decades, if coupled with other large-scale strategies such as renewable energies. These benefits are however outweighed by the radioactive danger associated to nuclear power plants, either in the context of the nuclear accidents that have already occurred or in that of the large amounts of long-lived nuclear waste that have been growing for decades and that represent a significant environmental and societal threat.

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1. Introduction

Nuclear energy is currently an important component of energy security and global economic development. It is one of the pillars of the world's energy needs, considering that in 2013 it covered 11% of global electricity, or 2477 TWh (terawatts hour) of the total 2013

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world energy production estimated at 23234 TWh (IEA, 2015). Nuclear power is therefore a viable power source given the increasing global energy demand, its high power supply capacity and the low fuel levels required for operation (Grandin et al., 2010).

Moreover, alongside renewable energy, nuclear energy is seen as a major opportunity for the decarbonization of global economies due to the fact that it is a low-carbon technology (NEA, 2015a). These technologies are essential, as today's society still largely (~80%) relies on fossil fuels, and fossil resources are projected to cover 50% of the total global energy supply up to 2050 (Don MacElroy, 2016). This large dominance of fossil fuels in the global energy sector has generated significant pressure onto the Earth's natural systems especially over the past five decades (1959–2010), during which it is estimated that 350 Gt C (gigatonnes or billion tonnes carbon) were released into the atmosphere (290 Gt C from fossil fuels and 60 Gt C from land use changes), of which 45% remained in the atmosphere (the other 55% was assimilated by the ocean and land areas), causing an accelerated climate warming (Ballantyne et al., 2012).

At present, more attention is being directed towards the relationship between nuclear energy and climate change (Verbruggen and Laes, 2015), considering that the climate system's perturbation is probably the most serious environmental problem in the world today (Rockström et al., 2009). Thus, it was suggested that this type of energy could be a major opportunity to improve some of these disturbances, by means of decarbonization and by stopping global warming at 2 °C above pre-industrial levels, which is the limit deemed necessary to ensure the stability of the Earth's biophysical systems (Fawcett et al., 2015). However, the condition for generating a clear effect on the decrease of atmospheric carbon is using the technology until 2050 in a mixed context, i.e. coupled with large-scale carbon capture and storage (CCS) and renewable technologies (NEA, 2015b). Therefore, even though a 17% increase in nuclear energy use is envisaged by 2050 (NEA, 2015b), without the simultaneous use of other viable strategies for eliminating atmospheric CO_2 emissions there can be no real chance of reducing global warming.

There is however a notable downside to nuclear energy – safety issues and the radioactive waste it generates. Even though it is known that nuclear power plants are safe systems, which have several built-in physical barriers conceived to prevent the escape of radioactive isotopes into the environment (Högberg, 2013), the past decades have shown that nuclear accidents can happen. Such instances include the well-known Chernobyl (1986) and Fukushima Daiichi (2011) events that released high amounts of radioactive isotopes into the environment, such as ^{137}Cs and ^{131}I (IAEA, 2012; UNSCEAR, 2008, 2013). Additionally, other risks can be associated to nuclear waste, which is highly radioactive and not easily storable safely and permanently. High-level radioactive waste is the most dangerous type, as it persists in the environment for up to one hundred thousand years (Horvath and Rachlew, 2016), which makes safe storage almost impossible.

Fortunately, nuclear waste management is rigorously regulated and controlled by the International Atomic Energy Agency – IAEA (and by other international organizations), the most important international entity that oversees nuclear activity globally (IAEA, 2006). In addition to the safety of radioactive waste storage facilities, this organization is also responsible for the cooperation between member states for nuclear development, and one of its primary roles is preventing the use of nuclear programs for military purposes (Prăvălie, 2014). Thus, IAEA was the main mechanism involved in the implementation of the 1968 Non-Proliferation Treaty, which was aimed at stemming the spread of military nuclear technology worldwide, except for five countries (United States, USSR/Russia, United Kingdom, France, and China) that were already nuclear powers at the time (Prăvălie, 2014).

This study aims to analyze the current state of global nuclear energy from three different angles – energetically, climatically and environmentally. This review paper, based on current relevant bibliographical sources and representative data, essentially aims to simultaneously assess the positive (energy security and support in fighting climate change) and negative (the risk of accidents and environment-related risks of spent nuclear fuel storage) effects of nuclear energy.

2. Past evolution of nuclear energy

The use of nuclear energy started in the early 50s, when the first nuclear reactor (a small unit called Experimental Breeder Reactor I) became operational at the Argonne National Laboratory in Idaho, United States. In the following years, the US, UK, Russia, France and Germany were the first to use nuclear technology commercially, and 20 other countries followed suit over the next decades (NEA, 2003). However, even though US president Dwight D. Eisenhower, in his famous “Atoms for Peace” UN speech, urged the international community as early as 1953 to cooperate in order to develop nuclear technology, atomic energy only underwent an ample international development phase almost 20 years later, in the early 70s (Fig. 1).

The most important global development stage in the history of nuclear energy therefore occurred roughly between 1970 and 1985, when the total number of nuclear reactors went from over 80 in 1970 to over 360 in 1985 (Fig. 1). While the number of operational nuclear reactors had an almost four-fold increase in this 15-year period, their installed power capacity had a much steeper 14-fold increase, i.e. from ~18000 MW in 1970–~250000 MW in 1985 (Fig. 1). This period corresponds to ~65% of atomic energy growth over six decades, when considering the increase in the number of nuclear reactors in 1970–1985 in relation to the entire analysed period 1955–2015.

The causes for the decrease in nuclear development after 1985 concern a series of events with global-scale effects, of which the most important are the increase of interest in oil after 1980 (as a result of price decreases) and especially the Chernobyl nuclear accident, which generated an obvious change in how countries worldwide viewed nuclear power (Albino et al., 2014). The effects of the 1986 nuclear disaster were so profound in both public and political spheres that, for instance, that same year Germany approved a resolution aimed at abandoning nuclear energy by the end of the decade, and the following year Italy completely shut down its nuclear energy program (Albino et al., 2014). In this context, Italy became the first country to go back to a “non-nuclear energy” status. Two other states followed its lead and abandoned their nuclear reactors in the following decades – Kazakhstan (1999) and Lithuania (2009) (Schneider et al., 2011).

However, several other states in Eastern Europe and Asia continued their nuclear energy projects after 1990, and went on to develop their nuclear capacity up to present day. Relevant such examples are Japan, South Korea, India, and China, which continued to build large fleets of nuclear reactors in the past two decades (Lovering et al., 2016). Nuclear energy technology therefore has kept on expanding up to present day globally (Fig. 1), and it is in fact going through a renaissance phase as a result of a notable rise in new power plant investments in developing economies, increases of fossil fuel prices and growing concern regarding climate change (Hedberg et al., 2010; Albino et al., 2014).

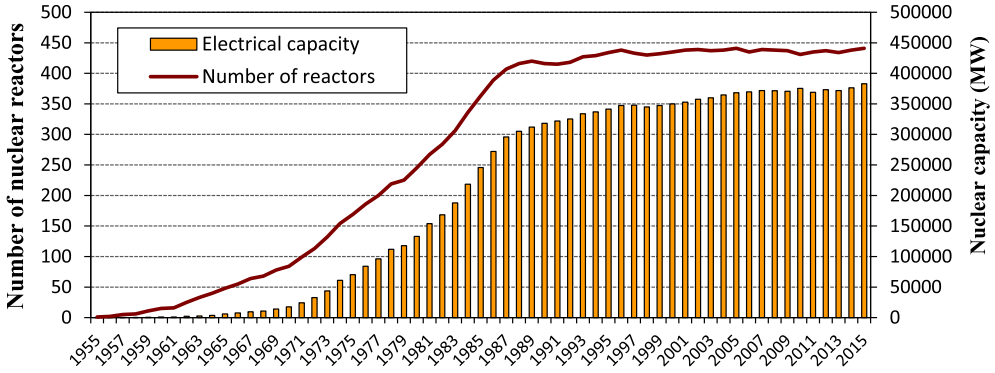

Fig. 1. Temporal worldwide variation of operational nuclear reactors and of their net capacity (MW) between 1955 and 2015 (data processing from https://www.statista.com/).

3. Current and future statuses of nuclear development in the world

According to the IAEA's Power Reactor Information System (PRIS), one of the most comprehensive and credible platforms in terms of statistical information on nuclear power plants worldwide (IAEA, 2005a), in 2015 there were 30 UN member states that used nuclear energy commercially (~16% of 193), or 31 countries, if also considering Taiwan, a partially recognized state (Fig. 2). Of these nuclear power countries, more than half are in Europe (Fig. 2), which reflects the fact that this continent has the most developed nuclear energy technology in the world. The 31 countries had in 2015 a grand total of 448 operational nuclear reactors, and the energy they produced covered ~11% of the total global commercially-generated electricity, a percentage that has remained stable in recent years (Schneider et al., 2015).

Of the entire global fleet of reactors, the United States has by far the highest number of nuclear reactors (99, 22% of 448), followed by France (58, 13%), Japan (48, 11%), Russia (35, 8%), China (31, 7%), South Korea (24, 5%) and India (21, 5%) (Fig. 3a). In terms of the net fleet capacity, it totals almost 387000 MW (or 387 GW) globally. Nationally, the countries with the highest nuclear electrical capacity are the United States (99185 MW, 26% of the total), France (63130 MW, 16%), Japan (42388 MW, 11%), China (26774 MW, 7%), Russia (25443 MW, 7%), South Korea (21733 MW, 6%) and Canada (13524 MW, 3%) (Fig. 3a).

The supplied nuclear electricity is also dynamic, as is its share of the total national electricity production. Therefore, given the absolute values of nuclear energy production, the top seven positions are the United States (798012 GWh, 33% of the total 2015 nuclear production of 2441331 GWh), France (419022 GWh, 17%), Russia (182807 GWh, 7%), China (161202 GWh, 7%), South Korea (157199 GWh, 6%), Canada (95637 GWh, 4%) and Germany (86810 GWh, 4%) (Fig. 3b). However, the top seven countries (according to the 2015 statistical data) in terms of nuclear energy share of the total national electricity production are France (76%), Ukraine (57%), Slovakia (56%), Hungary (53%), Slovenia (38%), Belgium (38%) and Armenia (35%) (Fig. 3b).

Given this overall picture of the electrical sector, Japan's case is particularly interesting – even though it is the third country worldwide in terms of nuclear energy potential (Fig. 3a), its 2015 energy production was among the lowest in the world (Fig. 3b). This is due to the government's decision to shut down all reactors countrywide after the 2011 Fukushima accident, which caused a severe national energy shock by reducing the nuclear power share from 31% in February 2011 to 0% in May 2012 (Hayashi and Hughes, 2013). In addition to the national effects related to higher fossil fuel imports (Vivoda, 2012), this disaster had implications that went beyond the country's energy security – internationally, e.g. the event generated a significant increase of investments in other energy sources such as liquefied natural gas (Hayashi and Hughes, 2013). There are however legitimate perspectives for nuclear energy production to be resumed in the immediate future, seeing as in 2015 two nuclear reactors were restarted under new safety standards set after the Fukushima accident (IEO, 2016).

In the near future, a worldwide atomic power expansion wave is closing in, as there are 60 reactors currently under construction in 16 countries (Fig. 3c). China is by far the world leader in this respect (20 reactors, with a projected net power capacity of 20500 MW), followed by Russia (7 reactors, 5520 MW), India (5 reactors, 2990 MW), United Arab Emirates (4 reactors, 5380 MW), United States (4 reactors, 4468 MW), South Korea (3 reactors, 4020 MW) and Pakistan (3 reactors, 2343 MW) (Fig. 3c). A third of all reactors under construction and of their projected capacity can therefore currently be found in China. It is interesting to note that two new countries, the United Arab Emirates and Belarus (Fig. 3c), will soon have operational nuclear plants, which raises the number of UN member states with nuclear energy status to 32, or 33 if the Taiwan non-member state is included.

In the following decades, some projections suggested a possible growth of global nuclear capacity even up to 1200 GW by 2050 (IEA, 2010), i.e. a nuclear expansion that exceeds 2015 levels by more than three times. This growth would require, on average, the construction of roughly 25 reactors every year (with a capacity of 1.5 GW per unit) after 2020, assuming that all currently operational reactors will have been decommissioned by the middle of this century (IEA, 2010; NEA, 2010a). However, even though this threshold is possible technically and industrially, certain unforeseen events such as nuclear accidents could considerably slow down the global nuclear power development in the next decades.

4. Decarbonisation potential in the global energy system

It was suggested that nuclear energy had considerably diminished the acceleration of global climate warming recorded in the past four decades, as its use prevented the release of over 60 billion tons CO_2 after 1970 (IAEA, 2016a,b). It is currently estimated that nuclear power is preventing the annual release of 1.2–2.4 Gt CO_2 emissions globally, assuming that, without this technology, more than 2400 TWh worth of nuclear power would be produced by natural gas combustion (which, on average, releases ~500 g CO_2/kWh) or coal combustion (~1000 g CO_2/kWh) (NEA, 2015b). In this context, nuclear power is considered to be an important contributor to the decarbonization of the global energy system.

Moreover, alongside renewable sources and CCS, nuclear power is also labelled a low-carbon technology (IPCC, 2013) due to the fact

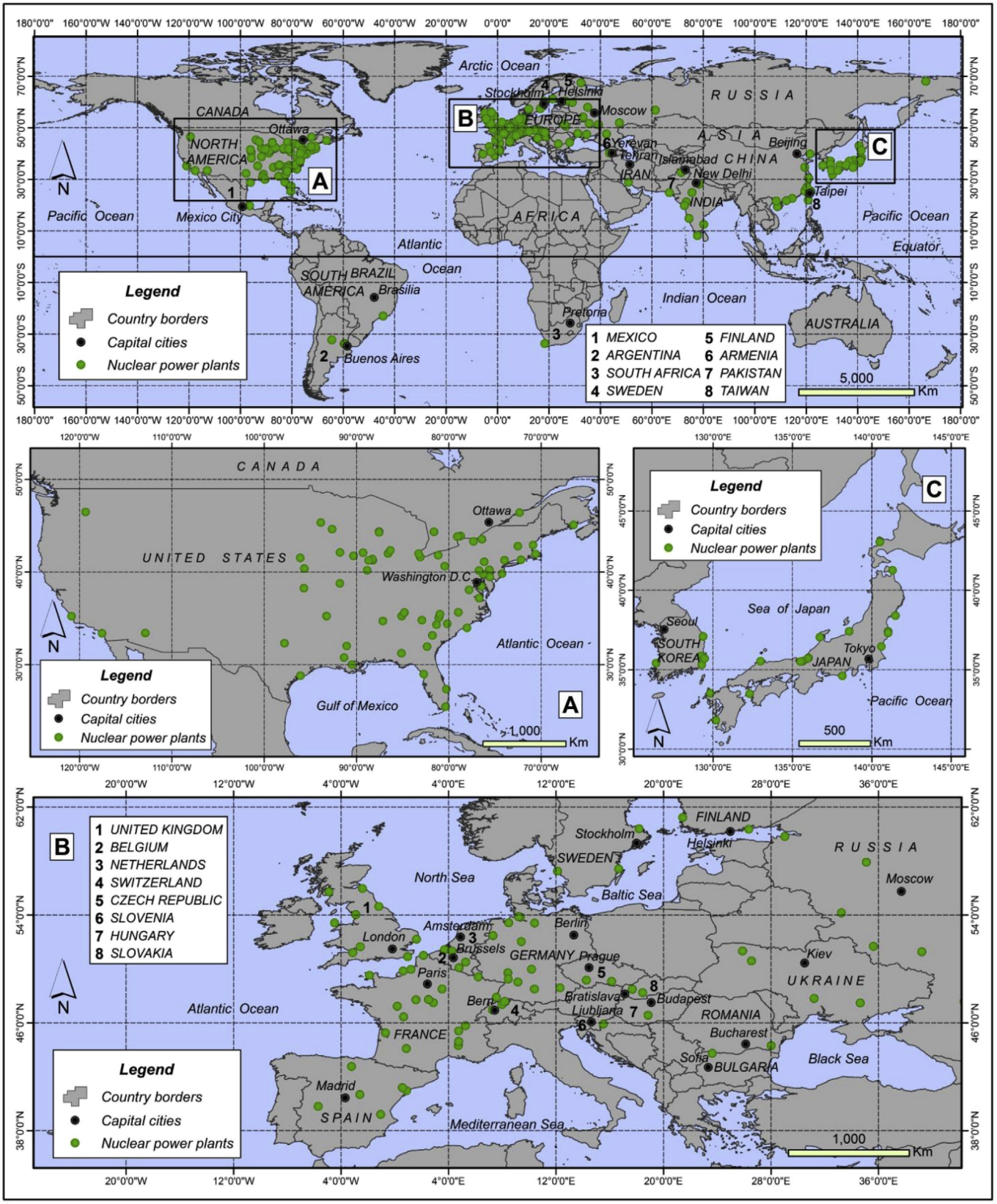

Fig. 2. Mapping of power plants with operational reactors in the world's nuclear power countries (data processing from https://www.iaea.org/pris/). Note: nuclear power plants were considered operational if at least one reactor was functional; the three rectangles (top) show regions in which a zoom was applied (middle, bottom) to enable a better view of the nuclear power plants spatial distribution.

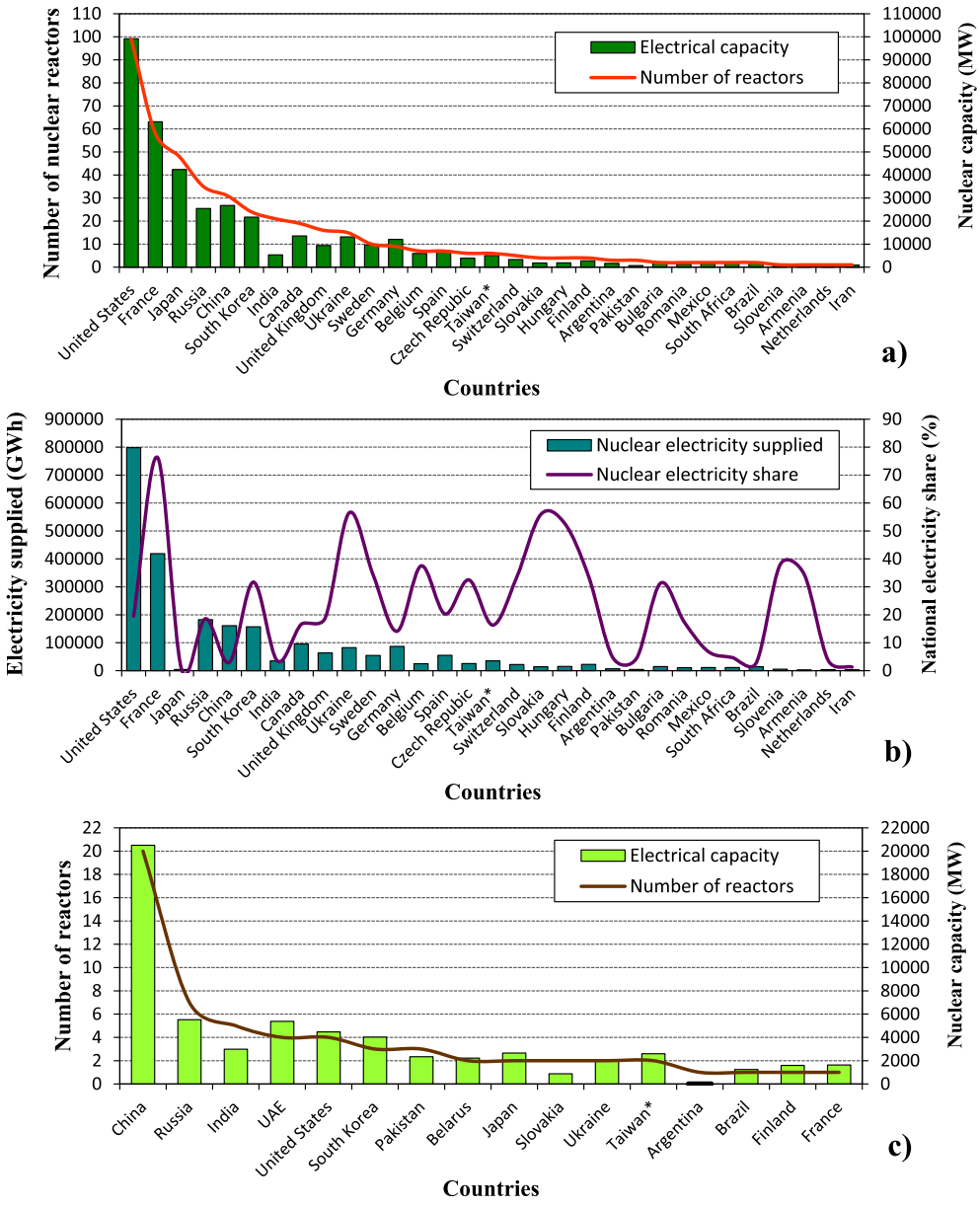
Number of nuclear reactors
Nuclear capacity (MW)
Electrical capacity
Number of reactors
United States France Japan Russia China South Korea India Canada United Kingdom Ukraine Sweden Germany Belgium Spain Czech Republic Taiwan* Switzerland Slovakia Hungary Finland Argentina Pakistan Bulgaria Romania Mexico South Africa Brazil Slovenia Armenia Netherlands Iran
a)
Countries
Electricity supplied (GWh)
National electricity share (%)
Nuclear electricity supplied
Nuclear electricity share
b)
Countries
Number of reactors
Nuclear capacity (MW)
Electrical capacity
Number of reactors
China Russia India UAE United States South Korea Pakistan Belarus Japan Slovakia Ukraine Taiwan* Argentina Brazil Finland France
c)
Countries

Fig. 3. Total number of operational nuclear reactors worldwide and their net capacity (MW) in 2015 (a); production of nuclear energy and the corresponding share of the total national power production in 2015 (b); number of nuclear reactors under construction worldwide (in the beginning of 2017) and their net capacity (MW) in the states that are currently expanding their nuclear energy infrastructure (c) (all data processing from https://www.iaea.org/pris/). Note: * states with disputed sovereignty; UAE – United Arab Emirates.

that the emissions of its entire life cycle are similar to those of renewable energy. Estimations show that the average quantity of CO_2 emissions per unit of electricity generated is currently 15 g CO_2/kwh (IEA, 2014) (Fig. 4a). This value is ~30/50/70 times smaller than the emissions generated by the combustion of gas/oil/coal, and is comparable to wind power emissions (Fig. 4a).

While low-carbon energies sources currently supply ~30% of electricity worldwide, this share must grow considerably for the energy system decarbonization to generate a concrete effect in stabilizing global climate warming at the 2 °C threshold set in relation to preindustrial levels (IAEA, 2015a, 2016a,b). To meet this objective and comply with the Paris Agreement, nuclear energy is being considered as a possible strategy for climate change mitigation, and is included in the work schedule of the Intergovernmental Panel on Climate Change. However, for it to become a viable option in line with the Paris Agreement 2 °C goal, a massive expansion of nuclear power capacity would be necessary in the following decades, i.e. from ~390 GW today to 930 GW in 2050 (NEA, 2015b). This growth would require an annual increase of the total nuclear capacity of ~20 GW after 2020, which will be difficult to achieve when considering the current nuclear expansion rate of up to 5 GW/yr since 2010 (NEA, 2015b).

In terms of its contribution to reducing carbon dioxide emissions in accordance with the 2 °C threshold, nuclear energy will have to contribute with a 13%-share reduction of CO_2 annually by 2050(NEA, 2015a) (Fig. 4b). This percentage corresponds to an absolute value of 2.5 Gt CO_2 per year, necessary for an effective decarbonization of the electricity sector (NEA, 2015a). In these conditions, nuclear power will provide some of the highest contributions to CO_2 reductions in the low-carbon energy spectrum

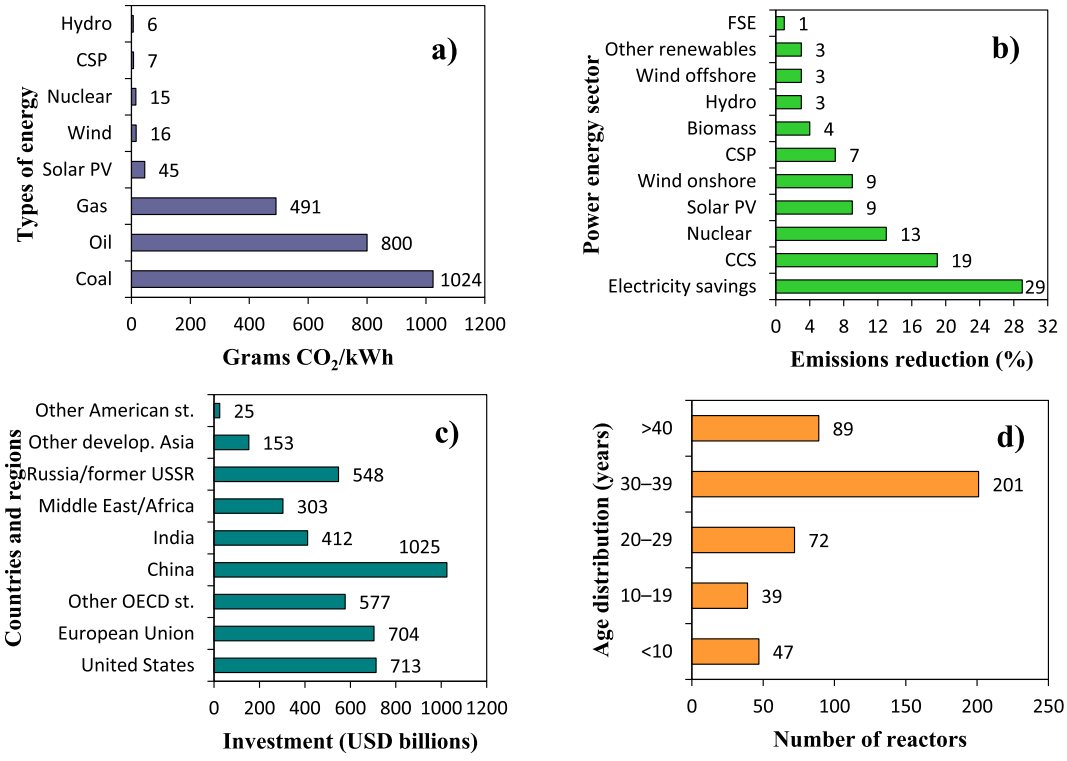

Fig. 4. Carbon dioxide emissions produced by 1 kWh electricity, according to different types of energy (a) (data processing from http://www.sfen.org/en/nuclear-for-climate); global emissions reduction required in the power sector in 2050 to keep the 2 °C warming target (b) (data processing from NEA, 2015a); global investment needs in nuclear energy between 2010 and 2050 for the 2 °C climate goal achievement (c) (data processing from NEA, 2015a); age distribution of operating global nuclear reactors (d) (data processing from https://www.iaea.org/pris/). Note: CSP – concentrated solar power; FSE – fuel switching and efficiency; CCS – carbon capture and storage; st. – states; develop. – developing; USSR – Union of Soviet Socialist Republics.

(Fig. 4b).

However, considerable investments are necessary to reach this target. It was suggested that, for reaching an installed nuclear capacity of 930 GW in 2050, a total investment of over USD 4 trillion would be necessary (NEA, 2015a), almost half of which (~USD 2 trillion) would be required for decommissioning nuclear facilities, extending the lifetime of power plants and expanding nuclear capacity in the OECD (Organization for Economic Co-operation and Development) countries, especially in the United States and the European Union (Fig. 4c). Outside OECD countries, China will have to invest roughly a quarter (~USD 1 trillion) of the total global amount in new nuclear capacity, thus becoming the country with the highest contribution to nuclear development by the middle of this century (Fig. 4c).

A significant part of these huge costs in OECD countries will be directed towards decommissioning power plants, seeing as, globally, about two thirds (290 units) of nuclear reactors are more than 30 years old (Fig. 4d), and 60% are located in three OECD countries – United States, Japan and France (IAEA, 2016a). The entire decommissioning activity (which includes nuclear facilities, used fuel and site restoration) is highly expensive – e.g. it is estimated that in the US such a procedure costs 500 million USD per reactor (IAEA, 2004; Chu and Majumdar, 2012). This is one of the main reasons why the country has extended the operating license of nuclear reactors from 30 (normal lifetime) to 60 years, and there are sources that say the US is even considering further extensions (IAEA, 2016a).

In addition to costs, another challenge for meeting the Paris Agreement goal could be the uranium supply capacity. It is to be expected that the upcoming nuclear development will require an expansion of the fuel cycle around the world, more specifically an increase of uranium mining production and enrichment capacities (IAEA, 2009). However, considering the stability of uranium resources, this nuclear fuel can provide support for the nuclear power increase – the most recent estimations suggest that there are currently 5.7 million tonnes of uranium in known reserves (NEA and IAEA, 2016). Considering the current exploitation rate of almost 57000 tonnes/year (IAEA, 2016a,b), it can be deduced that uranium resources will be sufficient for at least 100 years of nuclear electricity production.

In the end, it must be noted that even though nuclear energy is widely considered to be a low-carbon solution for climate change, this reputation is questionable (Kleiner, 2008). Considering the criterion of carbon dioxide emissions, the carbon footprint of the entire nuclear cycle might currently be underestimated (Kleiner, 2008; Sovacool, 2008). There are certain studies that show that the average emissions generated by this type of energy reach 66 g CO_2/kWh (Sovacool, 2008), i.e. significantly more than the generally estimations of 15 g CO_2/kwh (IEA, 2014). This value, four times higher than wind power emissions (Fig. 4a), is due to uranium processing (38%; e.g. mining or enrichment), decommissioning activities (18%), operation (17%), nuclear fuel processing and waste storage (15%) and nuclear power plant construction (12%) (Sovacool, 2008). However, even with these indirect emissions that are higher than the generally acknowledged estimations (but much lower compared to fossil fuel emissions), using nuclear energy in a mixed context, alongside renewable energies, could be a viable short- and medium-term solution for the global phase out of fossil fuels (Schiermeier et al., 2008; Chu and Majumdar, 2012; Hong et al., 2015).

5. Radioactive contamination. A major environmental issue of nuclear energy

Even though nuclear energy is considered to be beneficial for human society economically and, more recently, climatically, one of its major disadvantages with global-scale implications must be noted – the risk of environmental radioactive pollution (contamination). This risk can be approached in terms of two key facets: the threat of nuclear reactor accidents and the danger associated to nuclear waste management (the risk associated with nuclear weapons testing is not included in this review since the paper explores nuclear energy for commercial/peaceful purposes). Both can cause significant environmental and societal consequences in the unfortunate event that radionuclides from inside nuclear reactors or waste storage site facilities were to be released.

5.1. Nuclear reactor accidents

The past decades have proved that nuclear accidents can cause critical local, regional or global contamination. It is estimated that, after 1950, there were approximately 20 nuclear accidents worldwide in commercial (especially) and military reactors, which were linked to reactor core melting caused by cooling capacity system failures (Burns et al., 2012; Lelieveld et al., 2012). Upon analysis of the INES scale rating of these accidents (the International Nuclear and Radiological Event Scale), which groups nuclear events in seven classes based on their severity (the first three levels are called incidents, while the next 4 are called accidents) (IAEA, 2008), it can be noticed that throughout nuclear power history there have been 2 major accidents (maximum level – 7, Chernobyl and Fukushima), a single case of serious accident (level 6, Mayak) and several events classified as accidents with wider consequences (level 5), of which the most widely known is Three Mile Island (Table 1). However, even if the most severe cases (5, 6, 7) are fewer compared to low-intensity accidents (level 4), the former are the most alarming – the difference between one level and the next amounts to a ten-fold increase in severity (IAEA, 2008). In terms of frequency, the former USSR (almost a third) and the United States (a quarter) have the highest number of accidents by far (Table 1).

The Chernobyl accident (Ukraine) of April 26th, 1986 is known as the most severe nuclear disaster in civil nuclear power history, considering the large explosive release of radioactive material into the environment, as a result of human error (UNSCEAR, 1988, 2008; Burns et al., 2012). The explosion of reactor 4 caused the uncontrolled release of a considerable amount of radioactive isotopes into the atmosphere for ~10 days, which, due to atmospheric dispersion, contaminated extensive areas in the northern hemisphere, especially in Europe and the former Soviet Union (UNSCEAR, 2000, 2008). The most important released radionuclides (in terms of radiation dose delivered to the public) were ^{137}Cs and ^{131}I, and it is estimated that ~30% of the reactor core content of ^{137}Cs (or 85 petabecquerels – PBq, 1 peta = 10^{15}), and 60% of ^{131}I (1760 PBq) (Table 1) was transferred into the atmosphere (Lelieveld et al., 2012). Radioactive contamination with ^{137}Cs can be considered the accident's most drastic impact form (given the prolonged environmental persistence of this radionuclide, 30-year half-life), especially in former Soviet Union, where most of the ^{137}Cs deposition on the ground occurred (equivalent to ~40 PBq), distributed in Belarus (40%), the Russian Federation (35%) and Ukraine (24%) (UNSCEAR, 2008). At the same time, ^{131}I was a problematic radioactive isotope due to the fast transfer to the human food chain (via the transfer to pasture grass and subsequently to cow milk), despite its much lower persistence (8-day half-life) (UNSCEAR, 2008).

The Fukushima Daiichi accident (Japan) of March 11th, 2011, due to the Tohoku earthquake (magnitude 9.0) and subsequent tsunami (the waves were 14 m above sea level when they reached the nuclear power plant) that caused a power outage and the cooling system failure of reactors 1, 2 and 3, is considered the second most severe nuclear event in history (after Chernobyl) (Högberg, 2013; Steinhauser et al., 2014), and is also ranked on the top level of the INES scale (UNSCEAR, 2013; Sugiyama et al., 2016) (Table 1). A brief comparison of the two events shows that their socio-economic impact was very large; e.g. in terms of the people who had to be evacuated/relocated immediately (over 300000 relocated at Chernobyl, ~150000 evacuated at Fukushima), costs in billion USD (250–500 for Chernobyl, 100–500 for Fukushima) or the release of

Table 1
Nuclear accidents worldwide, their severity and radioactive atmospheric emissions–total and particular (PBq), exemplified with two representative radionuclides (adapted after Lelieveld et al., 2012).

No.[1]	Country	Location	Year of event	INES scale	Total radioactivity	^{137}Cs	^{131}I
1.	Canada	Chalk River	1952	5	>0.3	[2]	[2]
2.	USA	Idaho Falls	1955	4	[2]	[2]	[2]
3.	USSR	Mayak	1957	6	74–1850	[2]	[2]
4.	UK	Windscale	1957	5	1.6	0.02	0.7
5.	USA	Simi Valley	1959	5–6	>200[3]	[2]	[2]
6.	USA	Idaho Falls	1961	4	[2]	[2]	[2]
7.	USA	Monroe	1966	4	[2]	[2]	[2]
8.	Switzerland	Lucens	1969	4–5	[2]	[2]	[2]
9.	UK	Windscale	1973	4	[2]	[2]	[2]
10.	USSR	Leningrad	1974	4–5	[2]	[2]	[2]
11.	USSR	Leningrad	1974	4–5	55	[2]	[2]
12.	CSSR	Jaslovské Bohunice	1977	4	[2]	[2]	[2]
13.	USSR	Belojarsk	1977	5	[2]	[2]	[2]
14.	USA	Three Mile Island	1979	5	1.6[3]	[2]	<0.0007
15.	France	Saint-Laurent	1980	4	[2]	[2]	[2]
16.	USSR	Chernobyl	1982	5	[2]	[2]	[2]
17.	Argentina	Buenos Aires	1983	4	[2]	[2]	[2]
18.	USSR	Chernobyl	1986	7	>12 000	85	1760
19.	Japan	Tokaimura	1999	4	[2]	[2]	[2]
20.	Japan	Fukushima	2011	7	>630	12–37	190–380

[1] the events are listed in ascending order according to the year of occurrence.
[2] radionuclide emissions estimated indirectly by means of assumptions/no strong source of emissions/no data available.
[3] mainly/substantial emissions of ^{85}Kr; INES level 4 – accident with local consequences; INES level 5 – accident with wider consequences; INES level 6 – serious accident; INES level 7 – major accident; CSSR – Czechoslovak Socialist Republic.

radioactive substances (Högberg, 2013). In the last instance, considering the release of ^{137}Cs into the environment (atmosphere and ocean) due to the partial melting of the reactor cores in the days following the tsunami, it is estimated the total value reached 37 PBq (Table 1), which represents ~44% of Chernobyl emissions (Lelieveld et al., 2012). An important particularity of the Fukushima accident is that most of the radionuclides (about 80%) were deposited in the Pacific Ocean (either directly or indirectly due to the dispersion of radioactive substances over the North Pacific Ocean, after the initial release into the atmosphere) (Steinhauser et al., 2014; IAEA, 2015b), thus becoming a possible threat for marine ecosystems (due to aquatic biota transfers), and implicitly for the human population. Also, the contamination of some terrestrial waters and ecosystems (especially with radiocesium) was another possible threat for the public health (Kamei-Ishikawa et al., 2016; Laceby et al., 2016; Teramage et al., 2016). However, a recent study indicates this accident does not impose a significant radiological risk to the global public (in terms of effective dose), except for the Japanese nation (Lin et al., 2015).

Although the Mayak accident (Russia) of September 29th, 1957 is a highly severe nuclear event on the INES scale (level 6) that caused a large release of radionuclides (the most important of which is ^{90}Sr) especially in the Chelyabinsk region, this disaster is not representative for the nuclear reactor accidents in question because it was due to the chemical explosion of a storage tank with liquid radioactive wastes, which was part of a weapon material production complex (UNSCEAR, 2000). However, what is important for this section is the Three Mile Island nuclear plant accident (United States) of March 28th, 1979. The event, caused by the partial core melt of reactor 2 as a result of the deliberate shutdown of the cooling system (amid the occurrence of a pressure disturbance in the reactor system and a subsequent malfunction of a pressure control valve), released into the environment certain important radioactive fission products, e.g. noble gases, mainly ^{133}Xe (Högberg, 2013). However, only very small quantities of extremely dangerous radioactive substances (cesium, iodine) were released, as a result of successful efforts to maintain the nuclear reactor intact (Burns et al., 2012; Högberg, 2013).

There is currently a potential global risk of radioactive contamination in the hypothetical case of severe INES 7-type nuclear accidents. Based on advanced simulations, a very interesting study suggested that a major accident involving any reactor of the over 400 currently operational worldwide could affect extensive areas in Western Europe or Eastern Asia (due to the release of considerable amounts of radionuclides such as ^{137}Cs and ^{131}I), which would expose dozens of millions of people to radioactive contamination (Lelieveld et al., 2012). Considering the case of the radioactive isotope ^{137}Cs, representative due to its long persistence in the environment, it was found that, due to atmospheric dispersion, 8% would be deposited within a 50-km radius around the source, 30% within 500 km, 50% within 1000 km, and 25% within 2000 km (Lelieveld et al., 2012). Therefore, considering that over 90% of ^{137}Cs fallout will be transported within a 50-km radius around the source, as well as the fact that considerable amounts of radioactive particles will be deposited at distances of up to 2000 km, it can be concluded that any major nuclear accident could potentially cause significant environmental consequences regionally and even globally.

5.2. Nuclear waste management

The use of nuclear energy also poses an environmental and societal threat due to the difficult management of spent/used nuclear fuel waste. Although it is estimated that after 1971 reactors have produced a huge amount of high-level waste (HLW, waste that contains 95% of the nuclear power radioactivity, and consists mainly of uranium spent nuclear fuel) worldwide, i.e. ~350000 tons, a part of it has been reprocessed (reprocessing aims extract/recover the fissile elements of spent fuel, as well as the reduction of HLW volumes) (IEA, 2014). Also important are low- and intermediate-level waste, as well as the waste resulting from other stages of the fuel development cycle (mining, enrichment, fabrication), which are not factored into this large amount of HLW.

The current generation rate of the most dangerous nuclear waste (HLW) is alarming, i.e. ~12000 tons/year (Gerstner, 2009), considering that each reactor (of the 448 operational worldwide) produces about 25–30 tons HLW annually (IAEA, 2009; Rosa et al., 2010). At present, it is estimated that over 250000 tons HLW need safe permanent disposal worldwide, which is all the more important seeing as their radioactivity levels can remain high for up to one million years (Rosa et al., 2010). The need for disposal is most apparent in North America, where the amount of spent nuclear fuel was getting close to 100000 tons in 2007 in the United States and Canada (Fig. 5).

In this context, a way to partially solve the nuclear waste issue is reprocessing spent nuclear fuel. The global capacity of used nuclear fuel reprocessing is currently estimated at 5600 tons/year, and the largest reprocessing facilities are located in the United Kingdom (Sellafield, which covers 43% of global capacity), France (La Hague, 30%), Japan (Rokkasho, 14%), the Russian Federation (Mayak, 7%), India (Tarapur and Kalpakkam, 5%), and China (LanZhou, 1%) (IAEA, 2009). The United States is a particularly interesting case, as even though it is the largest producer of radioactive waste (Fig. 5), it does not have any such facilities anymore, having suspended spent fuel reprocessing back in 1977 (Mascarelli, 2009). However, although this procedure can reduce the volume of nuclear waste, the global amount of reprocessed waste is below half what is being produced annually and, additionally, it does not actually solve the urgent matter of long-term waste disposal (IEA, 2014).

Given this major challenge, the global political and scientific consensus on the most viable long-term management of highly radioactive waste is storage in deep geological repositories (NEA, 2010b). The procedure entails storing HLW at a depth of at least several hundred meters and isolating the waste with anthropogenic (e.g. especially-designed containers) and natural (e.g. underground locations with extremely low permeability surrounding rocks, in tectonically-stable areas) barriers, in order to minimize the risk of radionuclide release into the environment (IAEA, 2003). While this option is being considered in several nuclear countries (Table 2), such underground facilities have not been completed anywhere in the world (currently there are only temporary storage facilities) (IEA, 2014), although large-scale nuclear waste production dates back half a century. It is however only a matter of time before underground nuclear waste storage facilities will be built in the near future in countries such as Finland, France, Sweden and the US (Table 2), which have already made remarkable progress in implementing such projects. On a longer term, other countries (e.g. Canada, UK, Japan) might implement similar projects (Gibney, 2015).

Finland is currently in the most advanced stage in terms of HLW storage in a deep underground repository, as it is the first country in the world to approve in 2015 the construction of such a facility at Olkiluoto (south-west), where approximately 6500 tonnes of uranium will be stored (Gibney, 2015) starting around the year 2020 (Table 2). France is already getting ready to build the world's first underground repository for high- and medium-level long-term nuclear waste at Bure (in the northeast). Its opening is planned for 2025, and this will also be the largest repository in the world, as it will be able to store all of the country's high- and medium-level waste generated so far, as well as the waste that will be

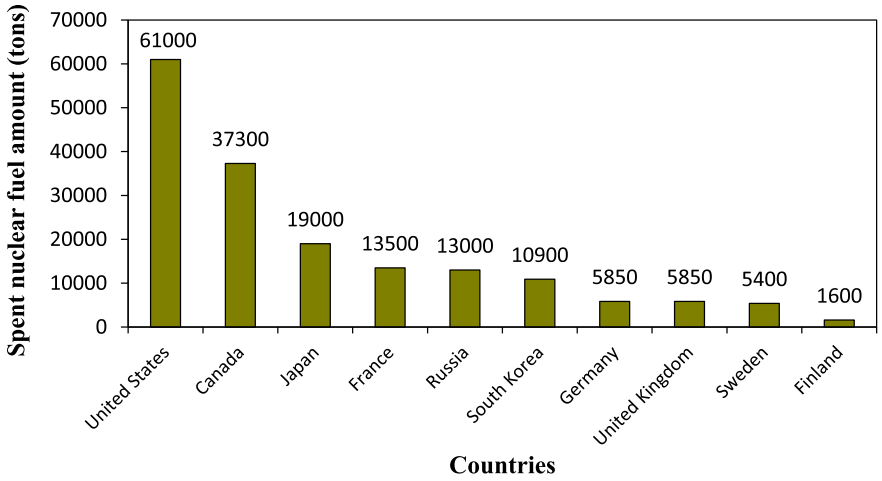

Fig. 5. Amount of nuclear waste (spent nuclear fuel) in 2007, in the top ten countries with highly radioactive nuclear waste (data processing from https://www.statista.com/).

Table 2
Storing and reprocessing of spent nuclear fuel and development perspectives for deep geological repositories in the top ten countries with highly radioactive nuclear waste (data processing after IEA, 2014; NEA, 2016; http://www.world-nuclear.org/).

No.	Country	Site storage	LIC[2]	Strategy	DGR[4] state	DGR develop. Perspective[5]
1.	US	RS[1]	LOM[3]	Direct disposal	Under construction	2021[a]
2.	Canada	RS	LOM	Direct disposal	Planned	2025[b]
3.	Japan	Rokkasho	N	Reprocessing	Planned	2035[b]
4.	France	RS, La Hague	LOM, N	Reprocessing	Under construction	2025[b]
5.	Russia	RS, Mayak, Zheleznogorsk	LOM, SW, S	Reprocessing	Considered	2025[c]
6.	South Korea	RS	LOM	Direct disposal	Considered	2028[d]
7.	Germany	RS, Ahaus, Gorleben	LOM, NW, N	Direct disposal	Considered	2031[d]
8.	UK	Sellafield	W	Reprocessing	Planned	2040[b]
9.	Sweden	Simpevarp	SE	Direct disposal	Under construction	2025[b]
10.	Finland	RS	LOM	Direct disposal	Under construction	2020[b]

Note: US – United States; UK – United Kingdom; 1 – Reactors site (the adjoining names represent central storage sites); 2 – Location in the country (N – north, S – south, W – west, NW – northwest, SW – southwest, SE – southeast; all these locations are related to the central storage sites); 3 – Location on the map (for the reactor sites, which can be identified in Fig. 2); 4 – Deep geological repository; 5 – DGR development perspective; a – timeline with expected construction end/entry into operation of the underground facility (underground repository suspended in 2009); b – timeline with expected construction end/entry into operation of the underground facility; c – timeline in which a decision is expected for the repository construction; d – timeline for the underground site selection process.

generated until 2030 (Butler, 2010). Sweden also plans to build an underground repository at Forsmark (in the east), which will become operational around 2025 (Näslund et al., 2013) (Table 2). The US has partial results in terms of deep geological facility development, seeing as the Yucca Mountain HLW storage site (southwest, Nevada) is not yet completed, even though the project was approved as early as 1987 and has so far totalled costs exceeding USD 10 billion (Mascarelli, 2009). This project, designed to store 70000 tonnes of nuclear waste (Mascarelli, 2009), was suspended due to geologic suitability issues identified after the project start (e.g. faster water flow at the site than initially expected) (Rosa et al., 2010), and it was even suggested that the site was selected in 1987 politically instead of scientifically (Butler, 2010). The halt of this ample project (that was supposed to start storing highly radioactive nuclear waste in 1998) and the lack of another concrete solution could represent a real threat to the country's environment and population. As mentioned before, the US has the highest amount of HLW in the world (Fig. 5), estimated at ~60000 tonnes (Rosa et al., 2010).

Therefore, the great amount of highly radioactive waste is one of the major environmental risks associated to nuclear energy, especially seeing as no country in the world currently has an appropriate management system in place for this type of waste. Even though in the following decades several deep geological disposal facilities will be built, they will only partially solve the radioactive pollution issue of the nuclear sector, both in terms of amounts (not all dangerous waste will be assimilated) and safety. For the latter, it must be noted that such facilities are not absolute barriers for nuclear waste, seeing as certain possible geological perturbations can be triggered over the course of hundreds of thousands of years of operation (Chapman and Hooper, 2012).

6. International nuclear energy policies

For decades, the nuclear energy sector has been under the aegis of various international initiatives that focus on industrial development and safety of use issues. Additionally, nuclear energy has lately been a topic of interest for international policies that outline major strategies for fighting climate change (NEA, 2015a,b), as it is considered to be a viable option for the decarbonization of the global energy system, alongside decreasing fossil fuel use, increasing energy efficiency, using carbon capture and storage systems and developing renewable energies (Pacala and Socolow, 2004). Nuclear power can therefore contribute to meeting the objectives of the most recent international climate change-related agreement – Paris Conference of the Parties (COP 21) to the United Nations Framework Convention on Climate Change (Rockström et al., 2017), which essentially aims to keep a global temperature rise this century well below 2 °C above pre-industrial levels (Fawcett et al., 2015). However, as previously mentioned, the

nuclear sector is primarily controlled by international policies that deal with technical-industrial development and safety regulations.

The most important international organization that oversees nuclear energy and technology, in terms of safe industrial operation and use for peaceful purposes, is the International Atomic Energy Agency. Founded in 1957 (Austria), this Vienna-based organization currently has over 160 member states (with or without nuclear programs) and is the only international institution active in the energy sources field that is affiliated to the United Nations (Heffron et al., 2016). This institution provides safety standards, technical guidelines and recommendations on all nuclear-related issues such as nuclear fuel cycles, reactor operations, radioactive waste management, human health and radiation protection.

One of the most important tools of the IAEA is the "Convention on Nuclear Safety" (entered into force in 1996), which promotes the high safety levels of global nuclear installations (IAEA, 2006). This is also ensured with the help of the "Operational Safety Review Team" program (founded in 1982), which aims to conduct thorough inspections of power plants (on safety of use) across the world by international specialists in the nuclear field (IAEA, 2005b). IAEA does however have other effective tools such as the "Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management" (entered into force in 2001, it is an important pillar for the appropriate management of nuclear waste based on a series of strict rules established internationally) and the "Convention on the Physical Protection of Nuclear Materials" (entered into force in 1987, amended in 2016) (IAEA, 2006). In the second instance, the physical protection of nuclear materials and facilities is constantly being tracked (in the use, storage and transport phases), which also covers the sabotage risk associated to nuclear materials – theft, contraband or nuclear terrorism.

Another highly important international body that focuses on the technical-industrial nuclear cooperation is the World Association of Nuclear Operators (WANO), founded in 1989. With its four main programs (peer reviews, operating experience, technical support and exchange, and professional and technical development), WANO tracks the activity and performance of nuclear power plants (and, implicitly, the safety of use) worldwide by conducting regular revisions and issuing technical reports (WANO, 2016). WANO can be considered an effective nuclear accident prevention mechanism, seeing as by 2009 all nuclear power plants worldwide had been peer-reviewed at least once. Additionally, after the Fukushima accident, WANO's objectives were extended from technical operational safety to include power plant design upgrades, while peer review activity was set to once every four years per nuclear power plant. The organization can also impose sanctions if operational safety rules are not followed (WANO, 2016). Other representative international organizations that play parallel roles in the nuclear industry and security cooperation are the World Nuclear Association and the World Institute for Nuclear Security.

The OECD Nuclear Energy Agency is another entity that plays a major role in the energy sector. Founded in 1958, this institution brings together 31 countries (most of which are nuclear power states that total 80% of the world's nuclear capacity) that cooperate in order to further develop the nuclear sector scientifically, technologically, environmentally and legally (NEA, 2015a). Other noteworthy parties that can influence directly or indirectly certain branches of the nuclear energy sector, with significant environmental and societal effects (e.g. radioactive waste management), include the International Commission on Radiological Protection (ICRP, 2007) and the European Commission (EC-JRC and EASAC, 2014).

International collaborations that focus on researching new advanced reactors are also part of international policies that can significantly influence the nuclear energy sector in the future. The most representative such example is the construction of new Generation IV reactors, which will generally be available in the next decade and will revolutionize nuclear fission energy by maximizing nuclear fuel efficiency and minimizing HLW generation (IAEA, 2009; NEA, 2014). They will be superior to currently advanced reactor models such as Generation III and III+, built after 1990 and 2000 (NEA, 2014). In order to complete the Generation IV reactors, several international initiatives have already been launched – e.g. "Generation IV International Forum" (in 2000), "International Project on Innovative Nuclear Reactors and Fuel Cycles" (2000), and the "European Sustainable Nuclear Industrial Initiative" (2010) (IAEA, 2009; NEA, 2014; Horvath and Rachlew, 2016).

However, on a longer term, a radical change is highly probable in the use of fission-based nuclear energy due to ongoing research efforts in nuclear fusion. The International Thermonuclear Experimental Reactor (ITER) is the most promising international nuclear fusion project. Initiated in 2005, it is funded by the European Union (for the most part), US, Russia, Japan, South Korea, China and India (Grandin et al., 2010; Castelvecchi and Tollefson, 2016). The project, which foresees the construction of a nuclear fusion reactor at Cadarache (southern France) and its entry into operation in 2020 in an experimental-demonstrative phase, is a real engineering challenge considering the fact that it involves the fusion of two isotopes of hydrogen under special conditions (tritium and deuterium, at temperatures of 150 million °C, ten times higher than the Sun's core temperature) in order to obtain helium (the process is similar to fusion reactions in the Sun), under the control of an intense magnetic field (Gerstner, 2009; Bigot, 2015; Horvath and Rachlew, 2016). Nuclear fusion could therefore enter large-scale use in the energy industry starting with 2050 (Horvath and Rachlew, 2016), especially considering some of its major advantages over nuclear fission, such as notably more supplied energy (~4 times more, considering for example that the energy released by 1 g of fusion fuel is equivalent to that of 12 tonnes of coal, while 1 g of fission/^{235}U fuel corresponds to that of ~3 tonnes of coal) (Grandin et al., 2010; Koelzer, 2013), and no generation of long-lived nuclear wastes (Gerstner, 2009).

7. Conclusions

As nuclear energy is highly controversial in today's society, it is important to analyze the role it plays for humanity in a multidimensional manner. Such an assessment is however difficult due to the complexity of the three dimensions of nuclear power this paper tackles – economic, climatic and environmental. The nuclear sector's role in global socio-economic development is currently uncertain, as its energetic and climatic advantages are outweighed by the disadvantages associated to radioactive pollution.

Therefore, in this review it was found that, economically, this energy remains for nuclear states an important power source option that will be kept on for at least several decades, considering the generally-employed practice of extending the operating lifetime of existing power plants, as well as the constantly growing nuclear infrastructure, with numerous new power plants currently under construction worldwide. Climatically, nuclear power is considered to be a major opportunity for decarbonizing the global energy sector, as the emissions of a nuclear power plant's entire life cycle are similar to those of renewable energies. It was therefore suggested that maintaining nuclear energy in a mixed global decarbonization strategy (increasing energy efficiency, decreasing fossil fuel use, using carbon capture and storage systems, and large-scale developing renewable energies) is a viable solution for keeping climate warming under the critical 2 °C threshold.

However, nuclear energy is associated to a real risk of nuclear

accident occurrence, as the past three decades have shown – two major accidents occurred (Chernobyl and Fukushima) that had considerable social (large-scale exposure of the public to ionizing radiation), environmental (regional and global radionuclide contamination) and economic (hundreds of billions of dollars in associated costs) consequences. Moreover, the very difficult management of highly radioactive nuclear waste that can last up to one million years is another critical issue the sector is facing. This state of affairs is aggravated by an apparent worldwide lack of interest in hazardous waste management, considering that underground facilities (for relatively safe storage) have yet to be built in the world, despite nuclear energy reaching maturity and the numerous related international policies.

Given the advantages and controversial nature of nuclear energy, it is difficult to draw a definite conclusion with regard to whether or not nuclear power should be promoted in future energy policies worldwide. However, considering the risk of nuclear accidents and the massive amount of highly radioactive waste being generated around the world, we believe fission-based nuclear energy should be phased out in the future. Although the risk of nuclear accidents tends to diminish as safer nuclear technologies are being promoted, the complicated issue of large-scale radioactive waste production remains. We must not forget we are already living in a world with over one quarter of a million tons of commercial long-lived nuclear waste that have been amassed throughout nuclear power history, which poses a real environmental and societal threat for both present and future generations.

In return, we recommend the systematic replacement of traditional nuclear energy with renewable sources and fusion-based nuclear power. We therefore don't propose to completely discard the fission-based nuclear sector from the global energy system, but to gradually replace it with fusion-based nuclear technology over the following decades, if will become operational by the middle of the century. If fusion-based nuclear energy become available commercially in the near future, its significant advantages would consist of strengthening global energy security (considering it is an extremely dense energy source) and clean electricity production, without generating long-lived nuclear waste. Given this context, the world's governments should continue/intensify their fusion electricity research and development efforts, as this could also be a major pathway in fighting global warming and, implicitly, other collateral environmental issues.

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